Phosphate Athermal Glass for Windows and Fibers
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Outline

- Program Objectives
- Benefits
- Design Considerations
- Schafer GlassDESIGN
- Schafer Approach
- Conclusions

Program Objectives

- Identify and formulate an athermal laser window material that has superior performance to Fused Silica
- Manufacture a prototype window using this material
  - ⇒ Design a prototype window, manufacture the glass blank, machine and polish the blank, and coat it such that it can be delivered for testing
- Phase II Program
  - ⇒ Fully characterize 3 athermal glasses produced in Phase I
  - ⇒ dn/dT, Modulus of Rupture, piezo-optic coefficients q_{11} and q_{12} , bulk absorption coefficient, thermal and mechanical properties
  - ⇒ Generate 2 additional high strength formulations for characterization

Benefits

- Benefits of Phosphate Glass:
  - ⇒ Athermal, Can Be Cast, Can Be Strengthened
  - ⇒ Low Cost and Rapid Manufacturing – Blanks Produced in 6-months;
  - ⇒ Provides alternative materials for other high power solid state lasers and the fiber optics industry

Significant Considerations

- TRANSMISSION: material must be highly transparent
- TRADESPACE: low absorption vs. low OPD
- SURVIVABILITY: thermal shock resistance and fracture toughness to be survivable

Schafer GlassDESIGN™ Code

- GlassDESIGN™ supports 28 different additives to phosphate
  - ⇒ 8.84×10^{30} combinations, ~infinite number of point designs
- Predicts index of refraction, dispersion, CTE, Young's Modulus, stress-optic coefficients (q_{11} and q_{12}), χ-, χ+ and χ_{eff}
  - ⇒ Excellent agreement between predictions/measurements
  - ⇒ CTE and dn/dT show correlation, as expected
- Used NIST strength data to guide some formulations
  - ⇒ Silica, alumina, yttria and boron oxide strengtheners
  - ⇒ Aluminosilicates and borosilicates are high strength materials found in nature
  - ⇒ http://www.ceramics.nist.gov/srd/summary/glspho.htm

Defining Figures of Merit

- Schafer Developed System and Material Level Figures of Merit
  - ⇒ Bulk Absorption
  - ⇒ Working stress, f(modulus and fracture toughness)
  - ⇒ OPD approaching zero
  - ⇒ Dispersion $D_o = n_f - n_c$
  - ⇒ Spectral transmission
- FOM = $[250(N_o - 1)/ A_o D_o] - 100$
  - ⇒ N_o is calculated refractive index, A_o is calculated CTE and D_o is calculated dispersion.
- Thermal Lensing Coefficient
  - ⇒ TLC = $dn/dT + (n - 1)(1 + \nu)\,\alpha + (n^3 \alpha E/4)(q_{11} + q_{12}) = \chi +$

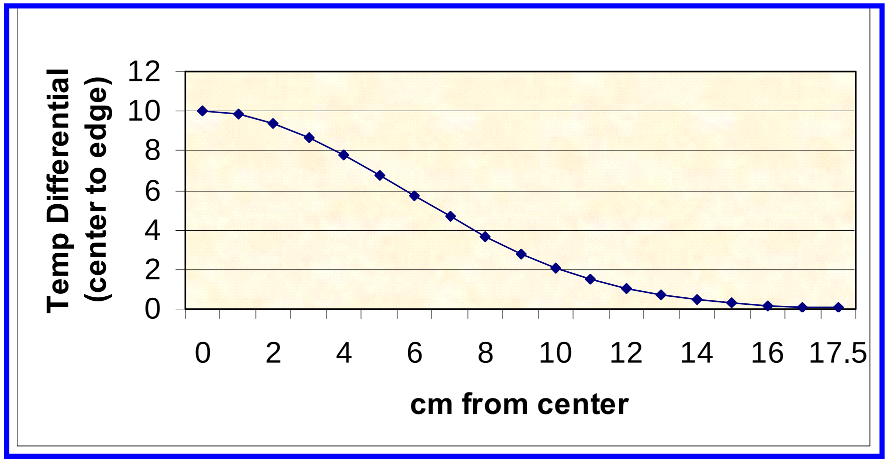
χ+ or χeffective?

- A material is athermal when χ+ = zero = Thermal Lensing Coefficient (TLC)
- Does use of χ+ instead of χeff perpetuate an error?
  - ⇒ $\chi_{eff} = |\chi_+| \times [1 + 0.75\,(\chi_-/\chi_+)^2]^{1/2}$
    - → $\chi_+ = dn/dT + (n-1)(1+\nu)\,\alpha + (n^3\alpha E/4)(q_{11} + q_{12})$ = TLC
    - → $\chi_- = (n^3\alpha E/4)\,(q_{11} - q_{12})$
- For an isotropic substance $q_{||} = q_{11}$ and $q_\perp = q_{12}$
- Typical, near athermal phosphate glass: q_{11} = 1.2E-06 and q_{12} = 2.2E-06 mm^2/N, index (n) = 1.557, E = 41.03E03 N/mm^2, α = 120.8E-07 K^{-1}, and dn/dT = -8.5E-06 K^{-1}
  - ⇒ χ_- = -4.676E-7 K^{-1}, χ_+ = 1.77E-05 K^{-1}, and χ_{eff} = 1.81E-5 K^{-1} = 1.025 χ_+.
- χ- must approach zero quicker than χ+, otherwise bracket term would approach infinity. Conversely, if χ+ goes to zero ahead of χ- the bracket term approaches unity and $\chi_{eff} = |\chi_+|$.
- χeff vs χ+ difference must be considered when working with crystals
- For amorphous, athermal phosphate glass the difference is negligible

OPD Analysis

• Assumed 2.54 cm thick, 35-cm diameter window.

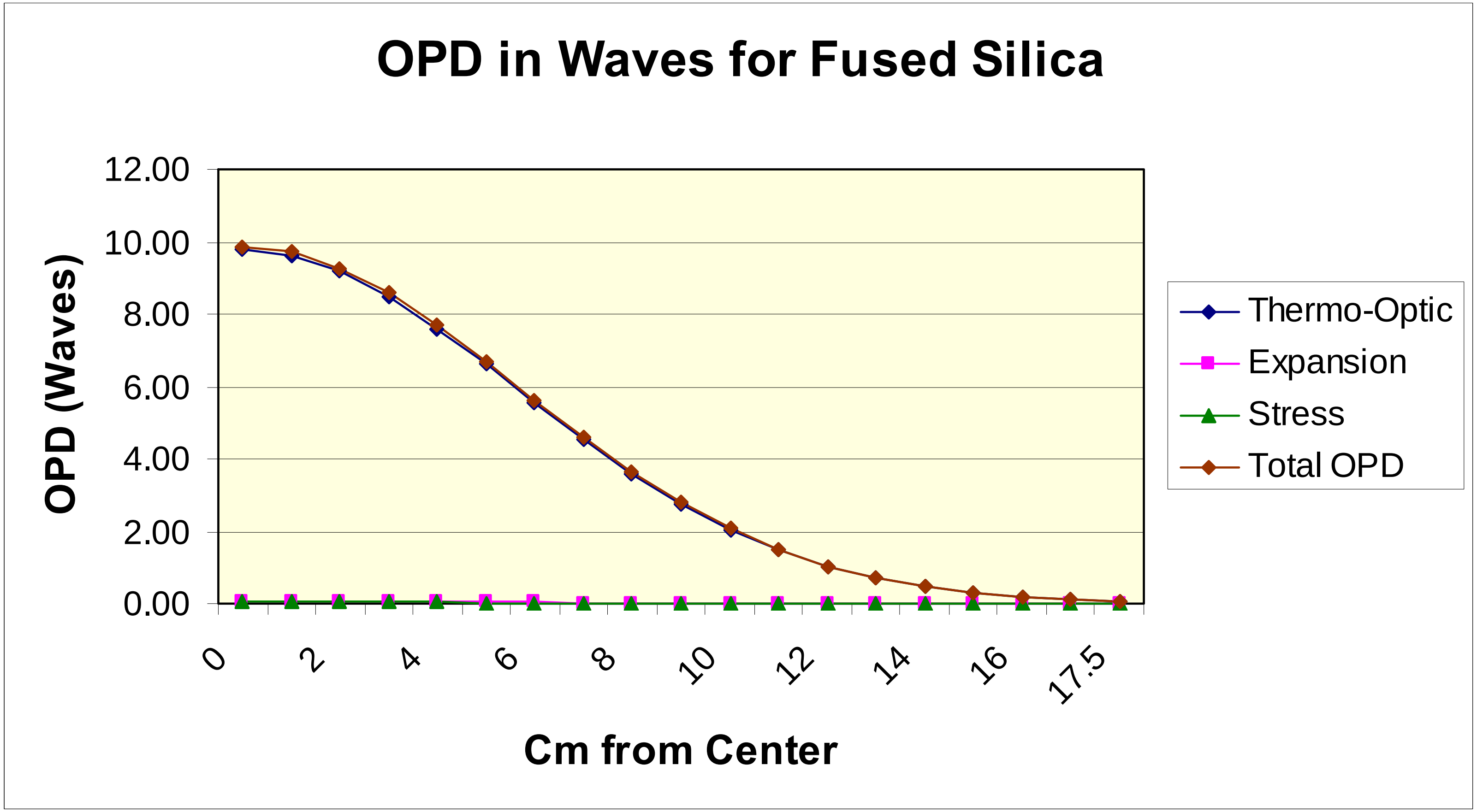
• Gaussian shaped temperature distribution with center temperature (peak) 10°C higher than the edges. Actual temperature distribution is f(beam profile, power, irradiation time, bulk absorption coefficient, and volumetric heat capacity).



• Waves OPD calculated using "Klein" formulation:

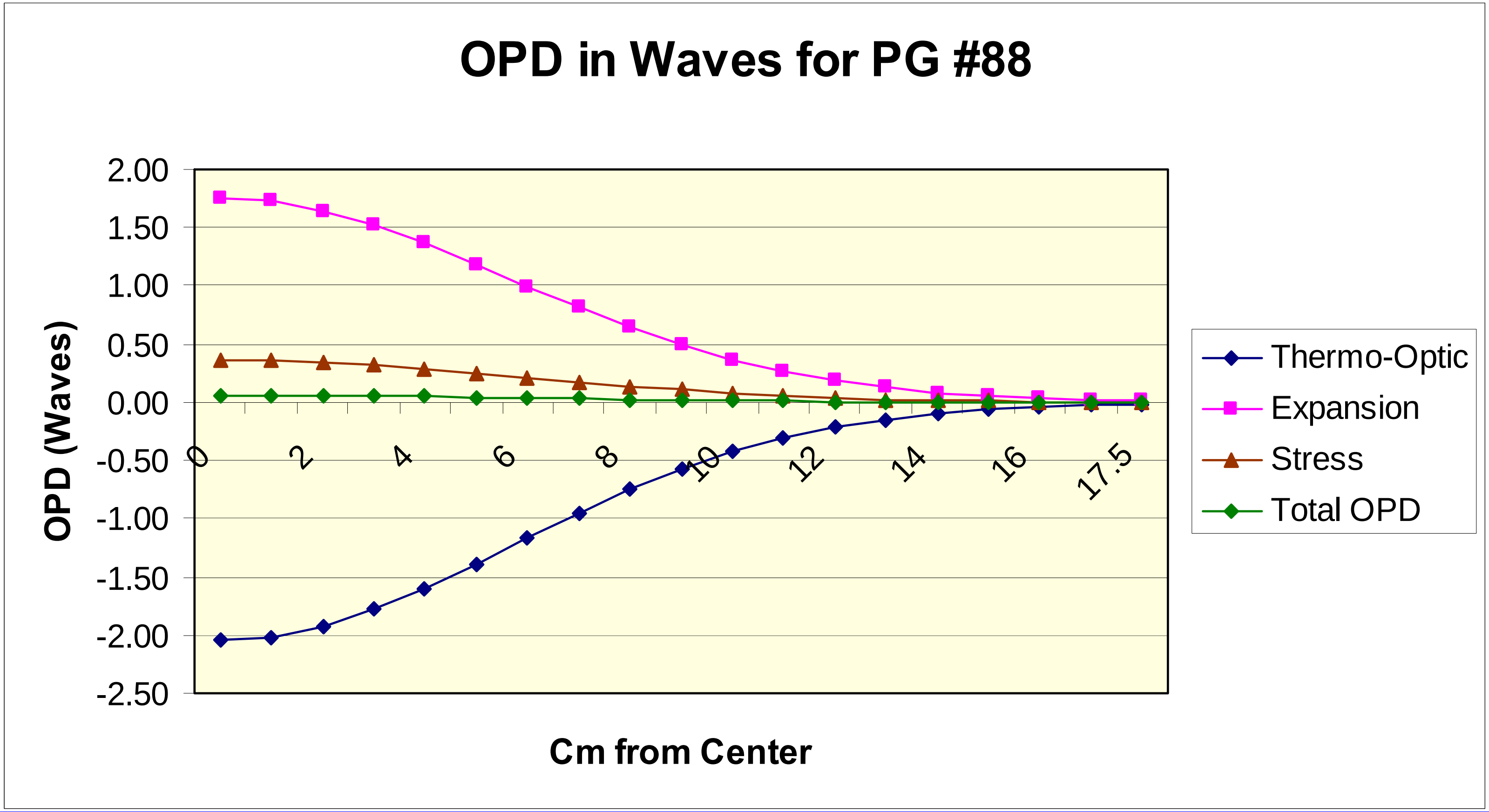
$$TLC = dn/dT + (n-1)(1+\nu)\,\alpha + (n^3\alpha E/4)(q_{11} + q_{12}) \text{ and}$$
$$OPD = (t\,\Delta T)/\lambda \times TLC$$

OPD Fused Silica



Low CTE
Positive Thermo-Optic Term Dominates OPD

OPD of Schafer PG 88



High CTE and Very Small Stress Term Cancelled by Very Negative Thermo-Optic Term
We Have Designed and Fabricated 8 Different Glasses Like This

Results

Glass	88c	106a	126a	136h	138i
Fracture Toughness ($MPa\text{-}m^{1/2}$) - Measured	0.58	0.44	0.45	0.51	0.52
MOR - Measured	106.7	83.6	103	101	97.9
Knoop Hardness ($HK_{0.2/20}$) - Measured	260.7	261	253.2	258.7	258
Young's Modulus - SGD Projected (GPa)	38.4	63.1	67.2	41.9	40.0
Young's Modulus - SGD Projected w/SiO_2 (GPa)	39.5	54.0	56.6	41.0	39.5
Young's Modulus - Measured (GPa)	37.23	39.52	38.91	37.57	38.47
Young's Modulus - SciGlass (GPa)	33.41	44.07	44.23	35.47	41.91
Poisson's Ratio (Measured)	0.2900	0.3000	0.2600	0.2800	0.2800
Poisson's Ratio (SciGlass)	0.2366	0.2350	0.2352	0.2253	0.2236
Elastic Property K SciGlass (GPa)	21.14	27.72	26.16	21.52	25.94
Glass Transformation Point (Tg) (^{o}C) - Measured	332	447	444	366	367
Glass Transformation Point (Tg) (^{o}C) - SciGlass	354	397	401	346	349
CTE - SGD Projected (K^{-1}) x 10^{-6}	16.15	14.66	14.84	16.00	15.65
CTE - SGD Projected (K^{-1}) x 10^{-6} with SiO_2	15.13	14.13	14.31	15.48	15.13
CTE - Measured (K^{-1}) x 10^{-6}	17.75	14.66	15.22	17.93	17.15
CTE - SciGlass (K^{-1}) x 10^{-6}	16.19	13.98	13.82	16.26	16.7

Results, cont.

Thermal Conductivity - Measured (W/m-K) @ 25°C	0.40	0.34	0.35	0.38	0.37
Thermal Conductivity - Measured (W/m-K) @ 90°C	0.43	0.36	0.37	0.40	0.39
Specific Heat (J/g-K) - Measured	0.640	0.480	0.500	0.580	0.610
Specific Heat (J/g-K) - SciGlass	0.648	0.501	0.511	0.575	0.580
dn/dT - SGD Projected (508 nm) x 10-6 (K^{-1})	-12.5	-12.2	-12.3	-12.95	-12.74
dn/dT - SGD Projected (508 nm) x 10-6 (K^{-1}) with SiO_2	-12.2	-11.6	-11.7	-12.4	-12.19
dn/dT - Measured (633 nm) x 10^{-6} (K^{-1}) - UDRI	-5.82	-3.2	-5.82	-4.66	4.82
dn/dT - Measured (1.54 μm) x 10^{-6} (K^{-1}) - SCHOTT	-13.2	-12	-12.4	-12.4	-11.9
dn/dT x 10^{-6} - SciGlass	-62.46	-38.72	-38.51	-63.21	-65.24
Bulk Absorption - Measured x 10^{-6} (cm^{-1})					
Refractive Index - SGD Projected	1.555	1.559	1.546	1.528	1.532
Refractive Index - SGD Projected with SiO_2	1.554	1.544	1.506	1.527	1.531
Refractive Index - Measured	1.526	1.569	1.558	1.526	1.535
Refractive Index - n_d @ 20°C - SciGlass	1.527	1.601	1.583	1.547	1.569
Density (g/cm^3) - Measured	2.92	3.596	3.488	3.112	3.18
Density (g/cm^3) - SciGlass	2.968	3.566	3.508	3.134	3.127

Summary and Conclusions

- Improved Figures of Merit for Material and System
- As-manufactured formulations have properties that are in excellent agreement with GlassDESIGN™ predictions
- Formulations have Excellent Transmission, Zero or Minimal OPD, Low Glass Transition Temperature for Manufacturability (Castable) and High Fracture Toughness for Survivability